LANDFORM DEGRADATION AND MASS WASTING ON THE ICY GALILEAN SATELLITES. J.M. Moore[1], E. Asphaug[1], D. Morrison[1], K.C. Bender[2], R.J. Sullivan[2], R. Greeley[2], P.E. Geissler[3], C.R. Chapman[4], C.B. Pilcher[5], and the Galileo SSI Team ([1]NASA Ames, MS 245-3, Moffett Field, CA 94035; [2]Geology Dept., Arizona State University, Tempe, AZ 85287; [3]LPL, University of Arizona, Tucson, AZ 85721; [4]SWRI, 1051 Walnut St., Suite 426, Boulder, CO 80302; [5]NASA Headquarters, Washington, D.C. 20546)

The geologic process of exogenic degradation operates to reduce the topographic relief of landforms by the movement of surface materials to a lower gravitational potential. In addition to the obvious role of gravity, exogenic degradation frequently utilizes abrasive mechanical erosion involving moving gas or fluids, often in combination with internal desaggregation of the relief-forming material through the loss (or deteriorating alteration) of its cohesive matrix. Exogenic degradation can be limited to slumping and mass wasting where there is no surface fluid or effective atmosphere.

The identification of specific landform types associated with mass wasting provides information about local sediment particle size and abundance and transportation processes. Generally, mass movements can be classified by the particle sizes of the transported material verses the speed the material moved during transport. Such a scheme has been successfully used to characterize mass movements on Mercury, Venus, the Moon, the Earth, and Mars, with the Earth and Mars as complicated cases involving elaborations of the simple criteria just described. Modifications of slopes on icy Galilean satellites (excluding impact-related crater modifications, such as terraced crater interiors) is not obvious in *Voyager* images. The improvement in resolution from *Venera 15/16* (~2 km/pixel) to *Magellan* (~150 m/pixel) was essential in the recognition and classification of mass movements on Venus (Malin, 1992). With this as a guide, *Galileo* images acquired at high (<100 m/pixel) resolution and low sun angle and/or in stereo were required to reveal landforms characteristic of mass movement. The objectives of this study have been to: 1) determine the extent and morphologic expression of landforms and surface textures that are indicative of exogenic degradation; 2) develop working hypotheses for the evolution of these landforms and surface materials; and 3) model the parameters of various hypotheses which can be tested against the body of observations.

Observations

Impact craters are the ubiquitous landform in the Solar System. Young km-scale impact craters have a common bowl-shape appearance when formed in rheologically brittle targets. Though individual craters are exogenic constructional features, cratering collectively operates to degrade pre-existing landforms (including of course other craters). Kilometer-scale craters on Ganymede's dark terrain (where *Galileo* has imaged it at <100 m/pixel) show a range of morphologies typical of landforms being degraded by the subsequent rain of smaller impacts. In contrast, the km-scale craters on Callisto (where examined by *Galileo* at <50 m/pixel) are characteristically rimed by bright material that seems to dissaggregate and the crater interiors fill with loose fine-grained dark material in a manner which resembles a decomposition of the bright high-standing blocks themselves rather than pulverization by small impacts. The loose fine-grained dark material appears to be a byproduct of bright material disintegration. Moreover, 100-m to km-scale craters on Callisto are underabundant relative to Ganymede dark terrain though both terrains are thought to be approximately the same age.

Both Ganymede and Callisto show a number of features attributable to classic down-slope mass movement. On Ganymede at least one rock or debris slide can be seen along a furrow scarp oversteepened by the formation of an impact crater at its base. Almost all slopes are covered by streamers of loose fine-grained dark material that collects to form deposits at scarp bases and fills local low-lying topography Additionally many crests or scarp-brinks of furrows and crater rims at two separate locations in Galileo Regio are traced by a thin lower-albedo line. If these lines are interpreted to be cracks or crevices filled with loose dark material, rather than the alternative that they are the expression of a dark stratigraphic layer exposed in walls of steep slopes, a possible cause of the cracks is the removal of material from under a competent surface layer causing a subsiding or overhang collapse. Two examples of brink crevices formed this way are: 1) on the ridges of terrestrial lava flows, created when molten lava is locally drained; and 2) along the edges of martian fretted channels, presumably created by a undercutting widening of the channel wall.

Several locations on Ganymede also exhibit distinctive erosion which apparently involves scarp retreat, etching, or pitting. In the 11 m/pixel images acquired on bright terrain at 30°N, 90°W rows of parallel-to-concentric rubble piles reminiscent of recessional moraines can be seen at the base of a scarp. In these images smooth-topped mesas seem to give way to a lower rubble plain. At this location there is a general underabundance of craters (relative to Galileo Regio) and many of those that are present appear eroded. In Galileo Regio the feature tentatively named Heliopolis Facula appears in detail to be composed of superposed brighter material that is forming a scarp-bounded plateau above the dark terrain. The bounding scarps are, in planview, irregular-to-crenulate, perhaps implying that the brighter material is undergoing erosion by scarp retreat.

On Callisto a possible example of a classic land or debris slide can be seen along one of the Valhalla scarps that was imaged at 37 m/pixel. The scarp height is ~300 m and the slide run-out is ~10 km. The images of the catena acquired at 33 m/pixel show that the sun-facing north wall has been retreated, losing much of its original planimetrically cuspate trace to become nearly straight. Along the north wall a texturally smooth pile of fine-grained loose material probably resting at the angle of repose can be seen at the base of retreating exposure of bright bedrock. The septa of the catena only extend about half-way from the anti-sunward south wall before they become indistinct and disappear. In several different widely-separated locations high-standing, fault-rotated km-scale blocks exhibit an unusual honeycomb texture that somewhat resembles ablation hollowing seen on terrestrial glaciers and solution weathering seen in some limestone landscapes.

Preliminary Speculation, Analysis, and Conclusions

The icy Galilean satellites show clear and unambiguous evidence of mass movements at variety of scales and perhaps employing a variety of mechanisms. In this section, speculation is given in order to foster creative discussion about what is producing these radically different landforms and surface textures. These speculations about candidate degradational processes will require further research and debate and so are offered as preliminary.

Degradational mass-wasting for much of Ganymede's dark terrain and some of Callisto's surface appears consistent with "dry" sliding of slumping, simple impact erosion, and regolith evolution. These "dry" slides and slumps appear mostly in the form of rock and debris movements, where gravity and an oversteepened slopes were all that is required to create these features. Here the term "dry" is being applied using a popular terrestrial mass movement classification scheme (e.g., see Coates, 1977, Malin, 1992) that plots material cohesion and particle size against speed of movement. This scheme thus tends to group mass movements requiring some short of fluidizing lubrication, whether that be from air or water, to one extreme and those which require no lubricant (and hence "dry") at the other..

In high resolution images of Callisto open stretches of landscape, far from any slopes, appear to be heavily and uniformly mantled by dark, loose, fine-grained, nearly cohesionless material. Aside from where the dark material is derived is the issue of how it could travel over large (10 km-scale) distances by gravity-driven down slope movement alone. In the absence of either a significant atmosphere or a surface liquid to provide lubrication, a reasonable candidate is electrostatic suspension, which has been identified as a potential geologic process on the Moon and asteroids (e.g., Lee, 1996).

The honeycombing and/or disaggregation of bright, high-standing blocks and crater rims on Callisto, as well as the appearance on Ganymede of features that can be interpreted as lowered, rubble-covered surfaces and retreated scarps may indicate the existence of an additional erosional process. On these satellites, where conditions are unfavorable for some of the processes which cause scarp retreat and surface lowering such as erosion by abrasion from wind, rainfall, or channelized running fluid, mechanical weakening of material exposed in the face of a scarp or in the surface of a pit may involve the loss of a cementing or matrix-forming material by sublimation. Moore et al. (1996) have proposed two end-member hypotheses or mechanisms for sublimation degradation. Case one is that of scarp retreat. Though observed on Io and Triton as well, the best currently imaged examples occur in martian south polar terrains where craters above scarp brinks are destroyed as the scarp retreats through them, leaving no trace on the surface below the scarp foot . The second end-member is that of scarp-bounded enclosed depressions or pits, such as exhibited by the etched terrain of the martian south polar region. The formation of the pits are speculated to be the result of the decay of thick but laterally limited lenses of volatile. Scarp retreat, on the other hand, is thought to be do to the progressive undermining of a of cap rock (or a surficial "cap" lag) underlain by an areally extensive layer of volatile-rich material. The modeling of Moore et al. (1996) found that the sublimation rate for any given volatile is strongly driven by insolation. The differential erosion (sun-facing vs. anti-sunward slopes) of the Callistan catena may be an example of the role of insolation in determining the rate of sublimation degradation. Modeling of several candidate icy Galilean satellite volatiles indicates that either a slow sublimator such as SO_2 or NH_3, or else a fast sublimator, such as CO_2, decaying out of a rate-retarding clathrate with H_2O, must be the responsible sublimate, for the surfaces of Ganymede and Callisto appear to have been undergoing erosion for a substantial portion of Solar System history. CO_2 has been tentatively identified on Ganymede and Callisto in NIMS spectra (Carlson et al., 1996). If verified, it, probably in clathrate form, may be the cement-forming sublimate.

References:

Coates, D.R. (1977) *Rev. Eng. Geol.*, 3, 3-28; Carlson, R. et al. (1996) *Science*, 274, 385-388; Lee, P. (1996) *Icarus* 124, 181-194; Malin, M.C. (1992) *JGR*, 97, 16337-16352; Moore, J.M. et al. (1996) *Icarus*, 122, p. 63-78.